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# Soils on igneous and metavolcanic rocks in the Sonoran Desert of Baja California, Mexico

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ABSTRACT

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Soils were examined on the widespread volcanic, plutonic and metavolcanic rocks within the Sonoran Desert of Baja California. In order to focus on in situ weathering and pedogenesis, most of the soils studied were on stable, nearly level summits. The combination of summit landscape positions and the aridic moisture regime tended to yield shallow soils, yet these soils display features of strong morphologic development, including eluvial horizons, subsoil clay increases, strong blocky and prismatic structure, reddish hues, and illuviation and stress argillans. Soils derived from volcanic materials are Paleargids with clayey natric horizons, saline subsoils, and petrocalcic horizons. Soils on granodiorite and metavolcanic rocks are loamy Haplargids that are neither saline nor sodic and are entirely noncalcareous. The granodiorite-derived soils had pH values as low as 4.0, apparently the result of metal sulfide weathering in the hydrothermally altered, ore-bearing rock. Torripsamments have formed in the reworked mantle of grus on an extensive tonalite pediment. Despite the variety of parent materials, smectite and kaolin are ubiquitous in the clay fraction of the soils. The smectites are dioctahedral and are neoformed and/or transformed from biotite or chlorite, depending on the parent material. The kaolin is largely the result of feldspar weathering. A Paleargid on rhyolite contained abundant palygorskite in the clay and silt fractions, particularly in association with the petrocalcic horizon. In all of the soils, oxalate-extractable Si plus Al was < 1% of the fine earth fraction. Most of the soils contained 2–3% dithionite-extractable Fe, but $Fe_d$ values were as high as 11% in the soil on metavolcanic rock. Goethite and hematite are the dominant Fe oxides, judging from low $Fe_o/Fe_d$ ratios and 10YR–2.5YR soil hues. Only the soils on basalt and rhyolite were calcareous, but the amount of $CaCO_3$ in the soils was unrelated to the Ca content of the rock, since these two rocks contained the most and the least amounts of Ca, respectively, of the five rock types represented in the study. Apparently, $CaCO_3$ accumulation in the soils is more dependent on dust contributions, possibly from nearby calcareous playa and fluvial sediments, than on in situ mineral weathering.

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## INTRODUCTION

The Sonoran Desert of Baja California is a region with very low rainfall, contrasting geology, and unique vegetation assemblages (Aschmann, 1967). The region is largely uninhabited and is poorly explored and inventoried. No pedologic research has been published for this area and, except for reconnaissance soils maps (Dirección General de Geografía del Territorio Nacional, 1982) there have been few investigations of the soils. As an initial step toward more comprehensive pedological and ecological studies, the objective of this research was to determine the characteristics of soils on the igneous and metavolcanic parent materials that dominate the Sonoran Desert landscapes in the state of Baja California. Where possible, the investigation was restricted to soils on summit positions so that mass movement influences would be minimal and the underlying rock would most likely reflect the unaltered parent material.

## MATERIALS AND METHODS

### *Study area description*

The study area is located in Baja California between the latitudes of 29°35′ and 30°10′N (Fig. 1). The Peninsular Ranges, extending south from southern California, make up the backbone of the peninsula and all sample locations fall within this region of mountains and central plateaus. The geology of the peninsula is generally divided into prebatholithic, batholitic, and postbatholithic terranes as described by Gastil et al. (1975). Within the study

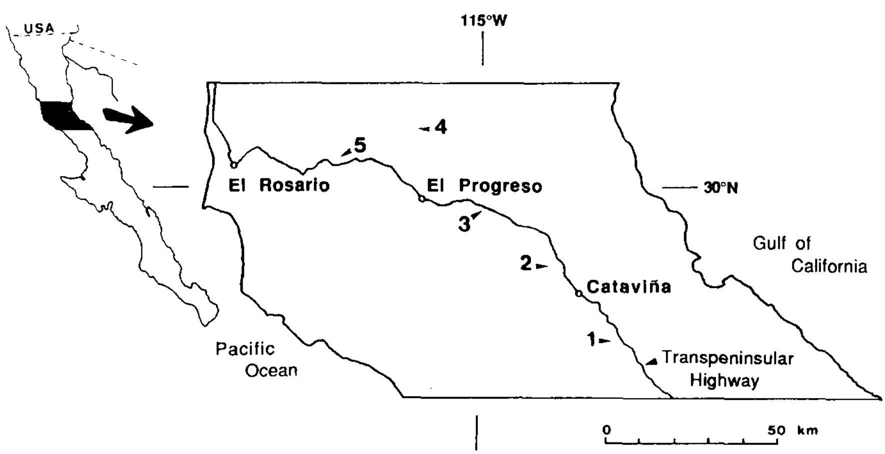


Fig. 1. Location of the study area on the Baja California peninsula. Pedon sites are labelled *1–5*.

area, the prebatholithic terrane is dominated by metamorphosed Mesozoic volcanic and volcaniclastic rocks of the Alisitos Formation. The exposed batholithic terrane in the state of Baja California is primarily tonalite (73% by area), but ranges in composition from granite to gabbro. The postbatholithic terrane is dominated by Miocene–Pliocene volcanic rocks, largely rhyolitic-andesitic in composition, and Pliocene–Pleistocene basalt and basaltic andesite.

The mean annual precipitation within the study area ranges from 137 mm at El Progreso to 113 mm at Cataviña (Reyes-Coca et al., 1990). Precipitation is in the form of rain, 80 to 90% of which falls during September through March (Reyes-Coca et al., 1990). Morning coastal fog extends across the region at times, particularly in the winter, providing additional moisture in the form of dew (Aschmann, 1967). Summer temperatures are hot and winters are relatively mild. At Cataviña, the hottest month is August, with mean maximum and minimum temperatures of 30 and 24°C, respectively. The coldest month is January,with mean maximum and minimum temperatures of 24 and 11°C, respectively.

The dominant plant species present at the sites are listed in Table 1. Most sites had similar communities with characteristic succulent species including *Agave* spp., *Fouquieria columnaris*, and *Opuntia* spp. Site 2 was a notable exception in that it lacked succulents.

### *Sampling and analysis*

Soils were sampled on five different kinds of rock at locations shown in Fig. 1 and described in Table 1. Whenever possible, pedons were described and sampled on the nearly level slopes of summit landscape positions. Soils were classified according to *Soil Taxonomy* (Soil Survey Staff, 1990). Bulk samples were air dried and sieved to remove coarse fragments (>2 mm). Particle-size distribution was determined by the pipet method without removal of Fe oxides (Gee and Bauder, 1986) and total carbon was determined by dry combustion (Nelson and Sommers, 1982). Soil pH was measured in saturated pastes and $CaCO_3$ equivalent was determined using a manometric method [Soil Conservation Service (SCS), 1984]. Organic carbon was calculated by subtracting carbonate-C from total-C. Electrical conductivity (EC) was measured in extracts of saturated pastes that had equilibrated overnight. Exchangeable cations were extracted with 1M $NH_4OAc$ at pH 7.0. Cation exchange capacity (CEC) was determined by saturating samples with NaOAc at pH 8.2, washing with 95% ethanol, and extracting with 1M $NH_4OAc$ to remove the adsorbed Na (SCS, 1984).

Citrate-bicarbonate-dithionite (CBD) and ammonium oxalate-in-the-dark extractions were made as described by Jackson et al. (1986) except that 2 g of soil were used. Total dissolution of rock samples for elemental analysis

TABLE 1

Location, classification and site characteristics of the pedons

| Site | Location | Soil classification | Lithology | Elevation (m) | Slope gradient (%) | Geomorphic position | Predominant vegetation |
|---|---|---|---|---|---|---|---|
| 1 | Mesa El Gato 18 km SE of Cataviña 29°35′N, 114°35′W | Fine, montmorillonitic, thermic Vertic Paleargid | Vesicular basalt | 900 | 5 | Summit of spur ridge | *Ambrosia chenopodifolia*, *Atriplex polycarpa*, *Encelia* sp., *Lycium* spp. |
| 2 | La Virgen 13 km NW of Cataviña 29°50′N, 114°47′N | Mixed, thermic, shallow Typic Torripsamment | Tonalite | 600 | 4 | Mantled pediment | *Agave deserti*, *Ambrosia chenopodifolia*, *Atriplex polycarpa*, *Larrea tridentata* |
| 3 | San Agustín 15 km E of El Progreso 29°56′N, 114°59′W | Fine, montmorillonitic, thermic Petrocalcic Paleargid | Rhyolite | 600 | 2 | Summit of mesa | *Atriplex* sp., *Encelia* sp., *Eriogonum* sp., *Viguiera* sp. |
| 4 | Cerro Blanco 20 km N of El Progreso 30°10′N, 115°12′W | Loamy, mixed, thermic, shallow Typic Haplargid | Metavolcanic (Alisitos Fm.) | 600 | 4 | Summit of small ridge | *Ambrosia dumosa*, *Atriplex* sp., *Lycium* sp., *Solanum hindsianum* |
| 5 | La Turquesa 30 km E of El Rosario 30°04′N, 115°27′W | Loamy, mixed, thermic, shallow Typic Haplargid | Granodiorite | 500 | 2 | Summit of small ridge | *Ambrosia chenopodifolia*, *Dalea* sp., *Haploppapus propinquus*, *Lotus* sp. |

followed the method of Bernas (1968). Elemental concentrations were measured by atomic absorption spectrophotometry.

Particle-size fractions were separated by centrifugation, sedimentation, and sieving, after pretreatment with 1M NaOAc (pH 5.0) to remove carbonates and soluble salts (Jackson, 1979) and NaOCl (pH 9.5) to remove organic matter (Anderson, 1963). Magnesium- and K-saturated clay samples were smeared on glass slides for X-ray diffraction (XRD) (Theisen and Harward, 1962). Freeze-dried clay powders were packed sideways in the shallow trough of an Al sample holder for measurement of d(060) spacings. Phyllosilicates with d(060) values of 1.50 to 1.48 Å are dioctahedral, while d(060) values of 1.55 to 1.53 Å indicate trioctahedral minerals (Brown and Brindley, 1980). Silts and finely ground sands and rock fragments were dried from acetone slurries onto glass slides. X-ray diffraction analyses were conducted using a Siemens D-500 diffractometer with Cu–K$\alpha$ radiation, a graphite crystal monochromator, a scintillation counter, and a Digital Equipment Corp. PDP 11/23+ computer linkage in stepscan mode.

Fine sands treated with CBD were mounted in immersion oil ($n = 1.544$) and at least 300 grains per sample were identified and counted by line transecting using a petrographic microscope. Thin sections of epoxy-impregnated argillic and Cr horizon material were examined with the petrographic microscope to distinguish stress and illuviation argillans according to criteria described by Brewer (1976).

## RESULTS AND DISCUSSION

### *Soils on volcanic rocks*

#### *Morphology*

Soils were studied on basalt (Site 1) and rhyolite (Site 3). Overall, these soils have greater morphologic development than the soils on other lithologies. Both have clayey, strongly structured Bt horizons which overlie thick, highly indurated petrocalcic horizons (Table 2; Fig. 2). The argillans identified in the field (Table 2) are stress argillans. Fine-textured, smectitic argillic horizons in arid regions typically lack illuviation argillans due to disruption by shrink–swell forces (Nettleton et al., 1969). The increase in subsoil clay in both soils meets argillic horizon criteria. In particular, the soil on basalt had the highest clay content (47%) of any of the soils analyzed. Within its clayey Bt horizons, this soil has strong, coarse, prismatic structure with peds separated by 5- to 10-mm-wide cracks that are up to 50 cm in vertical length, but that do not extend through the loamy A horizons to the surface.

Calcium carbonate accumulations in the soils range from fine soft masses or filaments in Bt horizons to petrocalcic horizons with Stage V carbonate morphology (Birkeland, 1984; modified from Gile et al., 1966) that are impenetrable with hand tools. The petrocalcic horizons consist of coarse plates,

TABLE 2

Morphologic characteristics of the soils

| Horizon | Depth (cm) | Color Dry | Color Moist | Texture | Structure[a] | Boundary[b] | Argillans[c] | Gravel (wt.%) | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| *Site 1 (basalt)* | | | | | | | | | |
| A1 | 0–2 | 7.5YR 6/4 | 7.5YR 5/4 | sil | 2fgr | as | –[d] | 26 | |
| A2 | 2–10 | 7.5YR 6/4 | 7.5YR 5/4 | sicl | 2fgr | aw | 1n po | 18 | |
| Btk1 | 10–27 | 7.5YR 5/4 | 7.5YR 4/4 | sic | 3cpr[e]→3csbk | gw | 3k po | 2 | Pressure faces on peds; carbonate filaments on ped faces |
| Btk2 | 27–51 | 7.5YR 5/4 | 7.5YR 4/6 | sic | 2cpr→3csbk | aw | 2mk po, gf | 7 | Soft carbonate masses |
| Btk3 | 51–67 | 7.5YR 5/4 | 7.5YR 4/4 | sic | 1csbk | aw | 2n po | <1 | Soft carbonate masses |
| Bkqm1 | 67–77 | 7.5YR 8/2 | ND[f] | | 3cpl | aw | – | | |
| Bk | 77–90 | 7.5YR 6/4 | 7.5YR 5/4 | sl | 2f, vfsbk | aw | – | | Soft carbonate masses |
| Bkqm2 | 90+ | Extremely hard indurated material; contains basalt rock fragments | | | | | | | |
| *Site 3 (rhyolite)* | | | | | | | | | |
| A1 | 0–2 | 7.5YR 4/4 | 7.5YR 4/4 | l | 2f, mpl | as | – | 25 | |
| ABtk | 2–8 | 7.5YR 5/4 | 7.5YR 4/3 | l | 2vf, fsbk | aw | 2n po, pf | 14 | Soft carbonate masses |
| Btk1 | 8–18 | 5YR 5/6 | 7.5YR 4/6 | cl | 3fsbk | aw | 2n, mk po, pf | 8 | Soft carbonate masses |
| Btk2 | 18–32 | 5YR 4/4 | 5YR 3/4 | sicl | 2cpr→3cpl | aw | 2n, mk po, pf | 1 | Soft carbonate masses and filaments |
| Bk1 | 32–36 | 7.5YR 8/2 | 7.5YR 7/2 | l | 1vfsbk | ab | – | 14 | |
| Bkqm1 | 36–47 | Indurated coarse platy material; contains rhyolite rock fragments | | | | | | | |
| Bk2 | 47–50 | 7.5YR 6/4 | 5YR 4/4 | sic | | | | | |
| Bkqm2 | 50–61+ | | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Site 2 (tonalite)* | | | | | | | | |
| A | 0–4 | 10YR 5/4 | 10YR 4/4 | lcs | 1f, msbk | as | – | 4 |
| C1 | 4–23 | 10YR 5/4 | 10YR 4/4 | lcs | massive | aw | – | 7 |
| C2 | 23–30 | 10YR 5/4 | 10YR 4/4 | lcs | 1fsbk | ai | – | 19 |
| Cr | 30–45+ | 7.5YR 5/8, 10YR 8/2 | ND | Weathered rock with 2n-k br clay films; can be dug with spade with difficulty | | | | |
| *Site 5 (granodiorite)* | | | | | | | | |
| A1 | 0–3 | 7.5YR 4/6 | 7.5YR 3/4 | sl | 2mpl | aw | – | 3 |
| A2 | 3–7 | 7.5YR 5/6 | 7.5YR 3/4 | sl | 2fsbk | aw | 2mkbr, 1mkpf | 5 |
| Bt1 | 7–12 | 5YR 4/4 | 5YR 3/3 | sl | 2fsbk | ab | 2mk, kbr, pf, po | 6 |
| E | 12–13 | 10YR 7/4 | 7.5YR 5/6 | ls | 3mcpr | bi | – | 5 |
| Bt2 | 13–23 | 2.5YR 4/6 | 2.5YR 3/6 | scl | 3mcpr | cw | 3kbr, pf, po | 5 |
| Cr | 23–45+ | 7.5YR 6/6 | 7.5YR 5/6 | Grus with fractures 10 cm apart containing red (2.5YR 4/6, dry) 3mk clay films | | | | |
| *Site 4 (metavolcanic)* | | | | | | | | |
| A | 0–4 | 10YR 5/4 | 10YR 4/4 | sl | 1f, msbk | as | – | 4 |
| Bt | 4–12 | 5YR 4/6 | 5YR 3/4 | sl | 2m, fsbk | aw | 2mkbr, pf, 2npo | 37 |
| BCt | 12–24 | 5YR 5/6 | 5YR 4/6 | sl | 1fsbk | cw | 2mk, kbr, pf, po | 64 |
| Cr | 24–45+ | Weathered bedrock with fractures 1–3 cm apart containing yellowish red (5YR 5/6) 2k, mk clay films | | | | | | |

[a]1 = weak; 2 = moderate; 3 = strong; vf = very fine; f = fine; m = medium; c = coarse; gr = granular; pr = prismatic; sbk = subangular blocky, pl = platy.
[b]a = abrupt; c = clear; g = gradual; b = broken; s = smooth; w = wavy; i = irregular.
[c]1 = few; 2 = common; 3 = many; n = thin; mk = moderately thin; k = thick; pf = ped faces; po = pores; br = bridging grains.
[d]– = none detected.
[e] = cracks 5–10 mm wide bounding prisms in the 10–60 cm depth.
[f]ND = not determined.

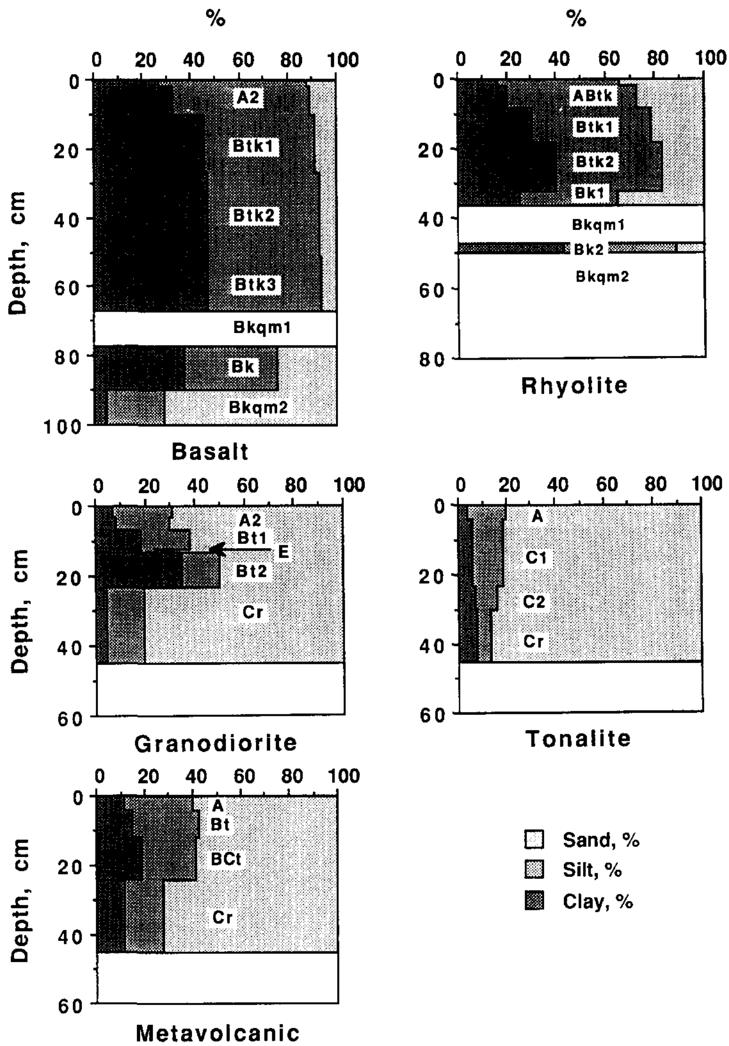


Fig. 2. Particle-size distributions for the pedons.

some of which contain laminar layers. Fragments of the petrocalcic horizons were unaffected by prolonged soaking in water, but did slake after soaking in HCl, which dissolved the calcite cement and left a residue of mineral grains and opaline silica cement. In both pedons, an uncemented Bk horizon (about 3–13 cm thick) was found between an upper plate and the underlying continuous petrocalcic horizon.

*Chemical properties*

The soils on basalt and rhyolite contain free $CaCO_3$ throughout and have Bk horizons that are dominated by $CaCO_3$ (Table 3). Although Ca is an ap-

TABLE 3

Chemical properties of the soils

| Horizon | Depth cm | Organic C (%) | pH | $CaCO_3$ equiv. (%) | EC ($dS\ m^{-1}$) | Extractable cations (1M $NH_4OAc$) ($cmol\ kg^{-1}$) | | | | CEC ($cmol\ kg^{-1}$) | Base saturation[a] (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Ca | Mg | Na | K | | |
| *Site 1 (basalt)* | | | | | | | | | | | |
| A1 | 0–2 | 0.41 | 7.48 | 7 | 0.9 | 60.6 | 4.0 | 0.7 | 2.2 | 35.9 | 188 |
| A2 | 2–10 | 0.15 | 7.70 | 7 | 0.5 | 61.2 | 4.0 | 0.4 | 1.6 | 37.8 | 178 |
| Btk1 | 10–27 | 0.00 | 7.92 | 9 | 0.7 | 59.2 | 3.9 | 4.8 | 1.1 | 38.1 | 181 |
| Btk2 | 27–51 | 0.13 | 7.90 | 9 | 3.2 | 58.0 | 3.2 | 11.5 | 0.9 | 38.2 | 193 |
| Btk3 | 51–67 | 0.00 | 7.94 | 9 | 5.1 | 53.8 | 3.0 | 14.0 | 0.8 | 38.0 | 188 |
| Bk | 77–90 | 0.00 | 7.67 | 39 | 9.4 | 48.7 | 4.2 | 10.9 | 0.6 | 10.3 | 625 |
| *Site 3 (rhyolite)* | | | | | | | | | | | |
| A | 0–2 | 0.22 | 7.79 | 2 | 0.8 | 22.8 | 2.3 | 0.9 | 1.1 | 27.0 | 100 |
| ABtk | 2–8 | 0.08 | 7.82 | 3 | 1.1 | 27.6 | 2.0 | 1.7 | 1.0 | 27.9 | 116 |
| Btk1 | 8–18 | 0.24 | 7.50 | 4 | 4.2 | 30.8 | 1.5 | 3.5 | 0.7 | 29.3 | 126 |
| Btk2 | 18–32 | 0.11 | 7.63 | 6 | 15.6 | 24.8 | 1.7 | 10.9 | 0.6 | 30.6 | 124 |
| Bk1 | 32–36 | 0.00 | 7.27 | 56 | 24.3 | 26.9 | 1.1 | 8.1 | 0.1 | 12.2 | 297 |
| Bk2 | 47–50 | 0.16 | 7.39 | 12 | 25.4 | 24.8 | 9.4 | 12.9 | 0.5 | 22.6 | 211 |
| *Site 2 (tonalite)* | | | | | | | | | | | |
| A | 0–4 | 0.39 | 6.78 | 0 | 0.6 | 5.1 | 1.9 | 0.1 | 0.4 | 7.0 | 107 |
| C1 | 4–23 | 0.22 | 6.74 | 0 | 0.2 | 4.9 | 1.8 | 0.1 | 0.4 | 7.9 | 91 |
| C2 | 23–30 | 0.15 | 6.78 | 0 | 0.2 | 5.0 | 2.0 | 0.2 | 0.4 | 7.7 | 99 |
| Cr | 30–45 | 0.18 | 6.83 | 0 | 0.4 | 3.8 | 1.5 | 0.1 | 0.8 | 6.7 | 93 |
| *Site 5 (granodiorite)* | | | | | | | | | | | |
| A1 | 0–3 | 0.44 | 6.33 | 0 | 0.8 | 5.0 | 3.8 | 0.3 | 0.5 | 11.3 | 85 |
| A2 | 3–7 | 0.18 | 6.27 | 0 | 0.5 | 5.5 | 4.0 | 0.3 | 0.4 | 11.3 | 90 |
| Bt1 | 7–12 | 0.22 | 5.05 | 0 | 0.5 | 7.8 | 5.1 | 1.1 | 0.2 | 15.8 | 90 |
| E | 12–13 | 0.19 | 5.43 | 0 | 0.9 | 3.1 | 1.7 | 0.8 | 0.1 | 8.6 | 66 |
| Bt2 | 13–23 | 0.25 | 4.12 | 0 | 0.6 | 11.0 | 7.6 | 2.5 | 0.2 | 25.9 | 82 |
| Cr | 23–45 | 0.06 | 4.55 | 0 | 0.7 | 7.3 | 2.3 | 1.7 | 0.1 | 18.0 | 63 |
| *Site 4 (metavolcanic)* | | | | | | | | | | | |
| A | 0–4 | 0.46 | 6.32 | 0 | 0.8 | 17.0 | 8.7 | 0.6 | 0.4 | 26.0 | 103 |
| Bt | 4–12 | 0.50 | 6.79 | 0 | 0.9 | 31.9 | 2.2 | 0.7 | 0.2 | 63.3 | 55 |
| BCt | 12–24 | 0.37 | 6.70 | 0 | 1.2 | 32.4 | 2.2 | 2.2 | 0.1 | 43.8 | 84 |
| Cr | 24–45 | 0.21 | 5.87 | 0 | 1.1 | 31.2 | 9.8 | 2.2 | 0.1 | 44.3 | 98 |

[a]Base saturation = Ca + Mg + Na + K extracted by 1M $NH_4OAc$ ÷ CEC. Base saturation > 100% indicates cation contributions from dissolution of soluble phase(s).

preciable component of the basalt, it is a minor element in the rhyolite (Table 4). Apparently, *in situ* mineral weathering is not the only process contributing Ca to form $CaCO_3$ in the soils; in fact, it may be a relatively minor source. Field observations at other locations within the study area indicate that soils

TABLE 4

Selected elemental components and XRD-detectable mineral components of bedrock samples from each pedon site

| Rock | Site | Si (%) | Al (%) | Fe (%) | Ca (%) | Mg (%) | Na (%) | K (%) | Minerals[a] |
|---|---|---|---|---|---|---|---|---|---|
| Basalt | 1 | 24.04 | 6.93 | 5.36 | 6.46 | 3.61 | 3.16 | 1.83 | F+++,OL++,M+,H+,CR |
| Rhyolite | 3 | 35.82 | 5.88 | 1.34 | 0.84 | 0.26 | 2.91 | 3.59 | F+++,CR++,Q++ |
| Tonalite | 2 | 31.85 | 8.37 | 2.08 | 3.14 | 0.71 | 3.84 | 1.00 | Q++,F++,M++ |
| Granodiorite | 5 | 33.07 | 6.48 | 3.60 | 2.44 | 0.57 | 3.13 | 1.35 | Q++,F++,H+ |
| Metavolcanic | 4 | 23.66 | 8.54 | 6.32 | 5.64 | 1.50 | 3.90 | 0.29 | F++,CH++,Q++ |

[a]CH = chlorite; CR = cristobalite; F = feldspar; H = hornblende; M = mica; OL = olivine; Q = quartz. Components are listed in order of decreasing abundance as estimated from X-ray diffraction patterns, +++ = > 50%, ++ = 10–50%, + = < 10%.

adjacent to playas have calcic horizons that are more developed and occur at shallower depths in the profile than those farther from playas. Similar trends in the Mojave Desert of California have been attributed to the accumulation of playa-derived $CaCO_3$-rich eolian dust (Reheis et al., 1989). Site 1 in our study is an upland position about 100 m above and 2 km southwest of a playa margin, while Site 3 is on a small mesa about 100 m above the surrounding calcareous fluvial sediments of the Llanos de San Agustín. Thus, both sites are near possible sources of eolian dust which may have been important contributors of $CaCO_3$ to the soils at these sites.

Calcium is probably the dominant exchangeable cation, although the $NH_4OAc$ extracting solution tends to dissolve $CaCO_3$, resulting in high Ca values and "base saturations" that exceed 100%. The $NH_4OAc$ solution has a similar effect with Na, extracting it from both exchange sites and soluble salts. Accumulation of Na and soluble salts in soils of arid regions is favored by deposition of salt-enriched eolian dust and by lack of leaching (Nettleton and Peterson, 1983). Still, the trend of extractable Na and EC increasing with depth in the soils at Sites 1 and 3 indicates that limited leaching has regularly occurred. Furthermore, extractable Na and EC values that are highest immediately above petrocalcic horizons indicate that wetting fronts occasionally reach these infiltration-restricting horizons. The pH of these soils ranges from 7.2 to 7.9, well below the pH values indicative of $Na_2CO_3$ (pH > 8.5).

*Mineralogy*

Vesicular basalt in an outcrop at Site 1 is composed of feldspar, olivine, mica, hornblende, and cristobalite (Table 4). The fine sand fraction of the soil contains a variety of primary minerals including quartz, feldspar, hornblende, and olivine (Table 5). The highly weathered grains that predominate in this size fraction are the weathering products of feldspar and mafic minerals. They are most abundant in the lowest horizon analyzed (Btk3) and

TABLE 5

Mineralogy of the fine sand (0.10–0.25 mm) fraction of selected horizons, all values in %[a]

| Horizon | W | Q | F | H | OP | G | M | CH | OL | PY | AP | EP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Site 1 (basalt)* | | | | | | | | | | | | |
| A1 | 59 | 10 | 4 | 8 | 1 | 1(v) | 1(b) | 3 | 11 | 1 | | |
| Btk1 | 59 | 9 | 9 | 9 | 1 | 1(v) | 2(b) | 2 | 9 | 1 | | |
| Btk3 | 74 | 5 | 4 | 4 | 1 | 4(v) | 1(b) | 2 | 4 | tr | | |
| *Site 3 (rhyolite)* | | | | | | | | | | | | |
| A | 27 | 3 | 57 | 5 | 2 | 2(p) | 3(b) | | | | 1 | |
| Btk2 | 20 | 5 | 66 | 3 | 2 | 2(p) | 3(b) | | | | 1 | |
| Bk2 | 19 | 5 | 70 | 4 | tr | tr(p) | 1 | | | | 1 | |
| *Site 2 (tonalite)* | | | | | | | | | | | | |
| A | 1 | 2 | 47 | 5 | 1 | 0 | 40(b) | tr | | | 2 | 2 |
| C1 | tr | 2 | 52 | 3 | 0 | 1(p) | 40(b) | 0 | | | 0 | 1 |
| Cr | tr | 2 | 29 | 2 | tr | 0 | 66(b) | 0 | | | 0 | 1 |
| *Site 5 (granodiorite)* | | | | | | | | | | | | |
| A1 | 19 | 0 | 65 | 4 | 8 | tr(p) | 3(b) | | | | | |
| Bt2 | 4 | tr | 80 | 6 | 8 | 1(p) | 1(b) | | | | | |
| Cr | 14 | 2 | 71 | 8 | 3 | 1(p) | 2(b) | | | | | |
| *Site 4 (metavolcanic)* | | | | | | | | | | | | |
| A | 83 | tr | 13 | 1 | 0 | 2(p) | 0 | | | | | 2 |
| Bt | 83 | 1 | 14 | 0 | 0 | 1(p) | 1 | | | | | 1 |
| Cr | 94 | 0 | 2 | 0 | 1 | 3(p) | 0 | | | | | 0 |

[a]Mineral abbreviations: W = unidentified weathered grain; Q = quartz; F = feldspar; H = hornblende; OP = opaque mineral; G = glass [(v) = volcanic, (p) = opal phytolith]; M = mica [(b) = biotite predominant]; CH = chlorite; OL = olivine; PY = pyroxene; AP = apatite; EP = epidote; tr = trace.

decrease in the upper part of the solum where the more intense chemical and physical weathering has reduced them to smaller size fractions. The minor amounts of volcanic glass shards that occur throughout the pedon (Table 5) may be inherited from the vesicular basalt or they may reflect pyroclastic contributions to the regolith. The presence of quartz in the soil (Tables 5 and 6), but not in the rock (Table 4), is further evidence that the basalt was not the sole parent material, even though vesicular basalt fragments were found throughout the pedon. Quartz is not abundant in the fine sand fraction, but its XRD peaks from the medium silt are much more intense than those of the other minerals present. The abundance of silt-size quartz suggests that eolian contributions have been important in the development of this soil.

Dioctahedral smectite predominates in the clay fraction of the soil on basalt, and is relatively less abundant in the medium silt fraction (Table 6). Considering its abundance, the smectite is probably largely neoformed from the dissolution products of feldspars and mafic minerals, but some of it may

TABLE 6

Mineral components of selected particle-size fractions as determined by X-ray diffraction[a]

| Horizon | Medium silt (5–20 μm) | Clay (<2 μm) |
|---|---|---|
| *Site 1 (basalt)* | | |
| A1 | Q+++, S++, F+, K+, M+, CR+ | S+++, K++, Q+, M+ |
| Btk1 | Q+++, F++, S+, M+, K+, CR+ | S+++, K++, M+, Q+ |
| Btk3 | Q+++, F++, S+, M+, K+, CR+ | S+++, K++, M+ |
| *Site 3 (rhyolite)* | | |
| A | Q+++, P++, F++, M+, S+, K+, CR+ | S+++, K++, P++, M++, Q++, F+ |
| Btk2 | Q+++, P++, F++, M+, S+, K+, CR+ | S+++, P++, K++, M+, Q+, F+ |
| Bk2 | Q+++, M++, F++, P++, K+, S+, CR+ | P+++, S++, K++, M++, Q+, F+ |
| *Site 2 (tonalite)* | | |
| A | M+++, F++, S+, Q+, K+ | M++, S++, K+ |
| C1 | M+++, F++, S+, Q+, K+ | S++, M++, K+ |
| Cr | M+++, F++, S++, K+ | S+++, M++ |
| *Site 5 (granodiorite)* | | |
| A1 | Q++, F++, M++, S++, H++, K+ | S+++, K++, M+ |
| Bt2 | F++, Q++, H++, S++, K+ | S+++, K++ |
| Cr | S++, F++, H++, Q+, K+ | S+++, K++ |
| *Site 4 (metavolcanic)* | | |
| A | F++, S++, Q+, K+, V+ | S++, K++, V++, F+, Q+ |
| Bt | F++, V++, S++, Q+, K+ | S++, V++, K++, F+, Q+ |
| Cr | S++, V++, F++, K+ | S++, V++, K++, F+ |

[a]CR = cristobalite; F = feldspar; H = hornblende; K = kaolin; M = mica; P = palygorskite; Q = quartz; S = smectite; V = vermiculite.
Components are listed in order of decreasing abundance as estimated from X-ray diffraction patterns; +++ = >50%, ++ = 10–50%, + = <10%.

be a transformation product of mica, particularly in the medium silt fraction. Kaolin is also present in both silt and clay fractions and is likely the result of feldspar weathering, since kaolinized feldspars were observed in the fine sand fraction.

Selective dissolution analyses provide information on the amorphous aluminosilica components and Fe oxides. Molar ratios of oxalate-extractable Si and Al ($Si_o/Al_o$) are about 0.5 throughout the profile, except in the $CaCO_3$-rich Bk horizon, where $Si_o$ is more abundant than $Al_o$ (Table 7). Allophane and/or imogolite are selectively dissolved by the oxalate extraction procedure and characteristically have $Si_o/Al_o$ ratios of 0.5–1.0 (Wada, 1989). However, the amount of oxalate-extractable Si and Al in this soil is minimal ($Si_o+Al_o<0.7\%$) and further evidence is warranted before allophane and imogolite are implicated.

Dithionite-extractable Fe ($Fe_d$) is uniform (2.3–2.5%) throughout most of the profile. The low $Fe_o/Fe_d$ ratios ($<0.1$; Table 7), indicate that the $Fe_d$ is largely from well-crystallized oxides. These results are consistent with the expected paucity of ferrihydrite and the predominance of hematite and goethite in hot, dry soils with low organic matter contents (Schwertmann, 1985). The secondary Fe oxides are weathering products of olivine and hornblende.

The rhyolite rock at Site 3 is composed of feldspar, cristobalite and quartz (Table 4). Alkali feldspar and plagioclase constitute 70% of the Cr horizon fine sand fraction, but decrease in abundance upward in the profile to 57% in the A1 horizon (Table 5). The trend of decreasing feldspar coincides with an increase in highly weathered grains which are weathering products of feldspar and mafic minerals. Quartz is relatively more abundant in the medium silt fraction (Table 6) than in the fine sand fraction (Table 5). Either quartz is smaller than fine sand in the parent rock, or it is the result of eolian deposition. Mica is present, but not particularly abundant, in sand, silt and clay fractions throughout the profile. It is either inherited from concentrations in the rock that are too low to be detected by XRD, or it is of eolian origin. Cristobalite, inherited from the parent rock, is a minor component of the medium silt and fine sand fractions. Fragments of opal phytoliths were present in each of the horizons analyzed (Table 5).

Dioctahedral smectite and kaolin are abundant in the clay fraction, but are minor components of the medium silt fraction. Palygorskite is abundant in both the silt and clay fractions, particularly in the Bk2 horizon from between petrocalcic slabs (Table 6). Although palygorskite occurrence in soils has been attributed to inheritance from parent materials, more recent evidence indicates that its formation is often favored in soil horizons enriched in secondary calcium carbonate (Singer, 1989; Monger and Daugherty, 1991). The distribution of palygorskite in the soil at Site 3 and its absence in the underlying rock suggest such a pedogenic origin.

Results of selective dissolution analyses for the soil on rhyolite are similar

TABLE 7

Data from oxalate ($Si_o$, $Al_o$, $Fe_o$) and dithionite ($Fe_d$) extractions of the soils

| Horizon | Depth (cm) | $Si_o$ (%) | $Al_o$ (%) | $Si_o/Al_o$[a] | $Fe_o$ (%) | $Fe_d$ (%) | $Fe_o/Fe_d$[a] |
|---|---|---|---|---|---|---|---|
| *Site 1 (basalt)* | | | | | | | |
| A1 | 0–2 | 0.21 | 0.40 | 0.50 | 0.22 | 2.45 | 0.09 |
| A2 | 2–10 | 0.24 | 0.42 | 0.55 | 0.21 | 2.45 | 0.09 |
| Btk1 | 10–27 | 0.15 | 0.28 | 0.51 | 0.13 | 2.39 | 0.05 |
| Btk2 | 27–51 | 0.15 | 0.28 | 0.51 | 0.13 | 2.37 | 0.05 |
| Btk3 | 51–67 | 0.15 | 0.26 | 0.55 | 0.12 | 2.28 | 0.05 |
| Bk | 77–90 | 0.08 | 0.05 | 1.54 | 0.02 | 1.44 | 0.01 |
| *Site 3 (rhyolite)* | | | | | | | |
| A | 0–2 | 0.17 | 0.32 | 0.51 | 0.27 | 2.90 | 0.09 |
| ABtk | 2–8 | 0.16 | 0.31 | 0.50 | 0.22 | 2.44 | 0.09 |
| Btk1 | 8–18 | 0.16 | 0.29 | 0.53 | 0.20 | 3.03 | 0.07 |
| Btk2 | 18–32 | 0.11 | 0.24 | 0.44 | 0.13 | 3.00 | 0.04 |
| Bk1 | 32–36 | 0.12 | 0.08 | 1.44 | 0.09 | 0.71 | 0.13 |
| Bk2 | 47–50 | 0.18 | 0.30 | 0.58 | 0.19 | 1.76 | 0.11 |
| *Site 2 (tonalite)* | | | | | | | |
| A | 0–4 | 0.09 | 0.13 | 0.66 | 0.14 | 2.14 | 0.07 |
| C1 | 4–23 | 0.09 | 0.13 | 0.66 | 0.13 | 2.00 | 0.07 |
| C2 | 23–30 | 0.12 | 0.10 | 1.15 | 0.09 | 1.89 | 0.05 |
| Cr | 30–45 | 0.07 | 0.05 | 1.34 | 0.04 | 1.86 | 0.02 |
| *Site 5 (granodiorite)* | | | | | | | |
| A1 | 0–3 | 0.16 | 0.17 | 0.90 | 0.33 | 4.68 | 0.07 |
| A2 | 3–7 | 0.07 | 0.14 | 0.48 | 0.29 | 5.31 | 0.05 |
| Bt1 | 7–12 | 0.05 | 0.16 | 0.30 | 0.33 | 5.75 | 0.06 |
| E | 12–13 | 0.00 | 0.10 | 0.00 | 0.16 | 3.73 | 0.04 |
| Bt2 | 13–23 | 0.02 | 0.21 | 0.09 | 0.18 | 3.98 | 0.05 |
| Cr | 23–45 | 0.00 | 0.73 | 0.00 | 0.08 | 3.63 | 0.02 |
| *Site 4 (metavolcanic)* | | | | | | | |
| A | 0–4 | 0.20 | 0.37 | 0.52 | 0.55 | 10.89 | 0.05 |
| Bt | 4–12 | 0.31 | 0.47 | 0.63 | 0.65 | 10.14 | 0.06 |
| BCt | 12–24 | 0.29 | 0.41 | 0.68 | 0.61 | 10.64 | 0.06 |
| Cr | 24–45 | 0.14 | 0.23 | 0.58 | 0.36 | 8.19 | 0.04 |

[a]Molar ratio.

to those for the soil on basalt (Table 7). Soil hues and $Fe_o/Fe_d$ ratios indicate that goethite and hematite are the dominant Fe oxides present, probably the weathering products of hornblende.

### *Classification*

Due to extremely limited rainfall, the soils of the Sonoran Desert in Baja California have an aridic moisture regime. The soils on volcanic rocks at Sites

1 and 3 have ochric epipedons, natric horizons, and petrocalcic horizons, leading to a great group classification of Paleargids. The soil on basalt (Site 1) has cracks that are 1 cm wide at the 50 cm depth and appears to meet the vertic subgroup criteria. The soil on rhyolite (Site 3) lacks such wide cracks and is in the petrocalcic subgroup. Both soils are in fine, montmorillonitic, and thermic family classes. Complete taxonomic names at the family level are given in Table 1.

*Soils on plutonic rocks*

*Morphology*

Soils were sampled on tonalite (Site 2) and granodiorite (Site 5). Site 2 is on a smooth slope between tors on an extensive tonalite pediment. Considering the geomorphic position, it is likely that the soil has formed in reworked grus and thus is not strictly residual, nor has it developed in a stable setting. In contrast, Site 5 is on the nearly level summit of a small ridge where the soil is residual. While the geomorphic regime of the pediment precludes strict comparison of the tonalite-derived soil with the more residual soils of this study, the soil is typical of the extensive tonalite pediments in the Sonoran Desert of Baja California.

The soil on tonalite shows very little morphologic differentiation. It has little or no structure and it lacks argillans, except in the Cr horizon where they form bridges between grains (Table 2). The texture is loamy sand throughout, with clay contents increasing with depth from 4% in the A horizon to 8% in the Cr horizon (Fig. 2).

In contrast, the soil on granodiorite is strongly developed. It has a red (2.5YR 4/6, dry) argillic horizon with strong columnar structure and many thick stress argillans. The Bt1 and Bt2 horizons have clay contents of 18 and 35%, respectively, but are separated by a broken, 1-cm-thick E horizon which comprises the tops and upper sides of the columnar peds in the Bt2 horizon. The E horizon has a lighter color, much less clay (6%), and lacks clay films compared to the Bt horizons (Table 2; Fig. 2). The Cr horizon consists of fractured rock that crumbles readily to grus. The abundant thick, red (2.5YR 4/6) illuviation argillans that coat the fracture surfaces indicate that current or past climatic conditions have supplied enough moisture for extensive clay illuviation.

*Chemical properties*

The pH of the tonalite-derived soil is uniformly 6.7 to 6.8, whereas the pH of the granodiorite-derived soil decreases from a high of 6.3 in the A horizons to a low of 4.1 in the Bt2 horizon immediately above the saprolite (Table 3). The soil pH values measured for 9 other pedons on the same granodiorite body, and within 2 km of Site 5, ranged from 5.9 to 4.0 (mean = 4.8). Depos-

its of metal ores in hydrothermally altered plutonic intrusions are locally common in this region (Gastil et al., 1975) and the area around Site 5 is known as La Turquesa because of turquoise deposits in the altered granodiorite. Weathering of metal sulfides, such as pyrite, associated with these ore bodies is the likely source of acidity in the soils, as is the case for acid soils on hydrothermally altered materials in the arid southwestern United States (Billings, 1950; Salisbury, 1964). The soils contain minimal soluble salts, as indicated by EC values $< 1$, and no $CaCO_3$. Calcium is generally the dominant cation on the exchange sites.

*Mineralogy*

The major mineral components of the tonalite at Site 2 are quartz, feldspar and biotite (Table 4). The fine sand fraction in the Cr horizon is largely biotite and feldspar (Table 5); whereas quartz is more abundant in coarser size fractions. Biotite content of the fine sand decreases in the A and C1 horizons due to weathering to smaller size fractions, while the more resistant feldspar nearly doubles in abundance.

The medium silt fraction, like the fine sand, is dominated by biotite and feldspar, but smectite and kaolinite are also present (Table 6). Smectite is more abundant in the clay fraction, especially in the Cr horizon (Table 6). Distinct d(060) XRD peaks at 1.53 and 1.50 Å from the Cr horizon clay indicate trioctahedral and dioctahedral phases, respectively. Of the two minerals present in the Cr horizon clay fraction, biotite is trioctahedral, thus the smectite must be dioctahedral. The smectite may have been neoformed, or it may have transformed from biotite. Biotite weathering transformations typically result in an increase in dioctahedral character through the loss of octahedral cations, along with a reduction in layer charge due to oxidation of octahedral Fe (Douglas, 1989). Compared to the Cr horizon, smectite is less abundant in the C1 and A horizons. Physical weathering of the grus has comminuted biotite, resulting in the dilution of other minerals in the silt and clay fractions.

Very little oxalate-extractable Si or Al was obtained from this soil ($Si_o + Al_o < 0.25\%$) (Table 7). The $Fe_d$ content ($\approx 2\%$) is nearly uniform throughout the profile. Goethite is the major secondary Fe oxide, judging from 10YR soil hues and low $Fe_o/Fe_d$ ratios. It is a product of biotite and hornblende weathering.

The major mineral components of the granodiorite at Site 5 are quartz, feldspar and hornblende (Table 4). The fine sand fraction of the soil (A1 and Bt2) horizons and the saprolite (Cr horizon) is dominantly feldspar, with notable amounts of magnetite (opaque), hornblende and highly altered grains (Table 5). The primary minerals detected in the rock were also prevalent in the medium silt fraction, along with the secondary minerals smectite and kaolin. The clay fraction is dominated by dioctahedral smectite, with substan-

tial kaolin. Mineral weathering is promoted by the low pH of the soil, while the lack of extensive leaching favors high solution concentrations of Si and base cations and subsequent neoformation of smectite. In addition to weathering, hydrothermal alterations may account for the formation of secondary minerals (McDaniel and Nielsen, 1985; Graham et al., 1988).

Molar $Si_o/Al_o$ ratios, as well as the $Si_o+Al_o$ values, are variable, but generally low (Table 7). On the other hand, Fe oxides are relatively abundant, with $Fe_d$ values of nearly 6%. Low $Fe_o/Fe_d$ ratios and 7.5YR–2.5YR hues indicate that hematite and goethite are the Fe oxide species present, apparently weathering products of hornblende and magnetite.

#### *Classification*

The tonalite-derived soil is sandy throughout, lacks significant morphologic development, and has a paralithic contact at the depth of 30 cm. It is classified as a mixed, thermic, shallow Typic Torripsamment (Table 1). A smaller proportion of the soils on the pediment at Site 2 had paralithic contacts deeper than 50 cm, in which case their classification differs only in that they are not shallow.

The granodiorite-derived soil has an ochric epipedon and an argillic horizon over a paralithic contact at the 23 cm depth. It is a loamy, mixed, thermic, shallow Typic Haplargid (Table 1).

### *Soils on metavolcanic rocks*

#### *Morphology*

The metavolcanic rock at Site 4 contains almost as much Ca as the basalt at Site 1 and almost seven times as much as the rhyolite at Site 3 (Table 4), yet no $CaCO_3$ has accumulated in the soils at Site 4, while those on the basalt and rhyolite are calcareous throughout and have petrocalcic horizons (Tables 2 and 3). This is further evidence that the release of Ca by *in situ* mineral weathering has been insufficient to produce calcareous soils in the study area. Although the rocky slopes of a limestone mountain are within several hundred meters of Site 4, they are apparently not an effective contributor of calcareous dust to the nearby soils on metavolcanic rock.

The soils on metavolcanic rock, as typified by the pedon at Site 4, have very gravelly, yellowish red (5YR 4/6 and 5/6, dry) argillic horizons with moderate blocky structure, common moderately thick and thick illuviation argillans, and nearly 20% clay (Table 2; Fig. 2). The soil sampled at Site 4 is underlain by highly fractured, weathered bedrock at a shallow depth. As in the Cr horizon of the granodiorite-derived soil (Site 5), the fracture surfaces are coated with clay films similar to those of the argillic horizon.

*Chemical properties*

The soil pH ranges between 5.9 and 6.8, and the EC values indicate very low levels of soluble salts (Table 3). The CEC values are higher than those of the other pedons analyzed, even though other pedons have horizons with twice as much clay. The high CECs result from appreciable smectite and vermiculite in the particle-size fractions coarser than clay as described below. Calcium and, to a lesser extent, Mg are the dominant cations on the exchange sites.

*Mineralogy*

The major minerals in the rock at Site 4 are feldspar, chlorite and quartz (Table 4). The fine sand fraction is composed overwhelmingly of highly weathered grains (Table 5), the products of feldspar and chlorite weathering. Chlorite transformation is probably the major source of the smectite and vermiculite in the medium silt and clay fractions (Table 6), while kaolin is the product of feldspar weathering, as evidenced by kaolinized feldspar grains observed optically in the fine sand fraction.

Molar $Si_o/Al_o$ ratios ranged from 0.5 to 0.7 and $Si_o+Al_o$ reached a maximum of nearly 0.8%, more than in any of the other soils examined (Table 7). Free iron oxides were abundant, with about 10% $Fe_d$ throughout, comprising hematite and goethite that probably formed during the weathering of Fe-rich chlorite.

*Classification*

The soil derived from metavolcanic rock has an ochric epipedon and an argillic horizon over a paralithic contact at the 24 cm depth. It is classified as a loamy, mixed, thermic, shallow Typic Haplargid (Table 1).

## SOIL GENESIS

Most arid regions have experienced profound climatic changes during the Quaternary, becoming warmer and drier in the Holocene than in the Pleistocene. Former pluvial climates are considered largely responsible for the development of Aridisols found on stable Pleistocene surfaces (Nettleton and Peterson, 1983). Paleobotanical evidence from packrat middens indicates that the late Wisconsin and early Holocene (23–8 kyr B.P.) climate of the Sonoran Desert yielded substantially more effective moisture than the modern climate (Van Devender, 1990), although most of the region would still be considered arid or semiarid throughout that time. Specific paleoclimatic information for central Baja California is scarce, but the available evidence indicates that prevailing conditions were similar to those for the Sonoran Desert in general. Packrat middens near Cataviña preserve juniper and chaparral materials from the early Holocene ($\approx 10$ kyr B.P.), indicating an effectively more moist climate than presently exists (Van Devender, 1990). The

Laguna Chapala basin (40 km southeast of our study area) is now dry, but once contained a lake at least 4.5 m deep, probably during the late Pleistocene (Arnold, 1957).

Except for soils on surfaces with active erosion and/or deposition, such as the tonalite pediment, the soils we examined had morphologic development commonly attributed to pluvial climates, including eluvial horizons, illuvial clay accumulation, strongly expressed subsoil structure, and subsoil reddening. In addition, the soils on volcanic rocks were calcareous throughout and had petrocalcic horizons and clayey, saline subsoils. The argillic and petrocalcic horizons of these Paleargids are no doubt Pleistocene relicts, while the subsoil salts and the $CaCO_3$ in the A and Bt horizons, can be attributed to Holocene and recent eolian additions (Nettleton and Peterson, 1983).

The character of the rock at each site has directly influenced some soil properties, such as the acidity of soils on hydrothermally altered granodiorite (Site 5), but it has not always had an overriding effect. For example, the basalt and rhyolite contain the most and least Ca, respectively, of the five lithologies addressed in this study, yet the soils on both of these rocks had extremely high $CaCO_3$ contents, while the soils on other rock types were noncalcareous. Although *in situ* mineral weathering is not discounted, the influx of eolian dust has been a more important source of $CaCO_3$, as has been demonstrated in other arid regions (Yaalon and Ganor, 1973; Reheis et al., 1989). Differences in soil development on Baja California landscapes are influenced by geographic location relative to atmospheric circulation patterns that deliver dust, as well as by parent rock composition and geomorphic position.

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